INCREASING QUALITY

UDC 658.56:666.1.038.1

MODELING THE TEMPERING OF AUTOMOBILE GLASS FOR DEVELOPING CORRECTIVE ACTIONS

R. I. Makarov,[1] E. V. Suvorov,[2] and Yu. M. Obukhov[2]

Translated from *Steklo i Keramika*, No. 1, pp. 3 – 5, January, 2010.

An algorithm for controlling the tempering process for automobile glass is simulated. It is shown that the mechanical properties of the glass produced can still be improved. The effectiveness of using modeling for developing corrective actions in the production of tempered glass is validated.

Key words: automobile glass, tempering process, control algorithm, improvement of mechanical properties.

Statistical analysis of tempered glass has revealed a substantial variance of the mechanical properties. The variation of the character of breakage reaches 21 – 30%. These characteristics largely depend on the tempering process, as is confirmed by regression models describing the dependence of the indicators on the tempering regime [1]:

maximum number fragments:

$$y_1 = 442.3 - 26.6x_{13} - 316.4x_{18} - 8.0x_{19}; \quad (1)$$

largest length of fragments (mm):

$$y_2 = -196.5 + 6.0x_{13} + 154.8x_{18} + 1.6x_{19} + 0.25x_6; \quad (2)$$

minimum number of fragments:

$$y_3 = 140.4 - 0.4x_{11} - 102.4x_{18} - 2.5x_{19} + 0.4x_9, \quad (3)$$

where x_{13} is the number of flows; x_{18}) interval 2 left-hand; x_{19}) height of punch, mm; x_6) vault temperature in chamber 2 in zone 2 of the tempering furnace, °C; x_{11}) temperature in chamber 4 in zone 12, °C; x_9) temperature in chamber 3 in zone 11, °C.

The quality of the glass produced can be increased by controlling the tempering regime. Control is a multicriterional decision-making problem. A decision made for correcting a regime is evaluated by a set of criteria characterizing the mechanical properties of the glass, as determined by the requirements of GOST 5727–88. The problem of controlling the technological tempering process can be formulated as follows:

minimize the linear form of the criterion

$$\mathrm{K} = C_1 y_1 + C_2 y_2 + C_3 y_3, \quad (4)$$

where C_1 and C_2 are coefficients, under the constraints

$$y_1 \le y_{1,\,\mathrm{pr}}; \quad (5)$$

$$y_2 \le y_{2,\,\mathrm{pr}}; \quad (6)$$

$$y_3 \le y_{3,\,\mathrm{pr}}. \quad (7)$$

All regime variables x_i must fall within admissible limits:

$$x_{i,\,\min} \le x_i \le x_{i,\,\max}. \quad (8)$$

The criterion (4) is determined by the requirements imposed on the character of the breakage of the glass during the tests. The maximum number of fragments y_1 and their largest length y_2 must not exceed prescribed values $y_{1,\,\mathrm{pr}}$ and $y_{2,\,\mathrm{pr}}$. The inequality (7) limits the minimum number of fragments during tests which must not be less than $y_{3,\,\mathrm{pr}}$.

The inequality (8) reflects the need to pick a regime x_i from the region prescribed by the system of limitations. The regime variables x_i will be found in the region described by the regression equations (1) – (3).

The problem (4) – (8) formulated above is a typical linear-programming problem and can be solved by well-known methods.

[1] Vladimir State University, Vladimir, Russia (E-mail: makarov.ruslan1955@gmail.com).
[2] AGC Bor Glass Plant JSC, Bor, Russia.

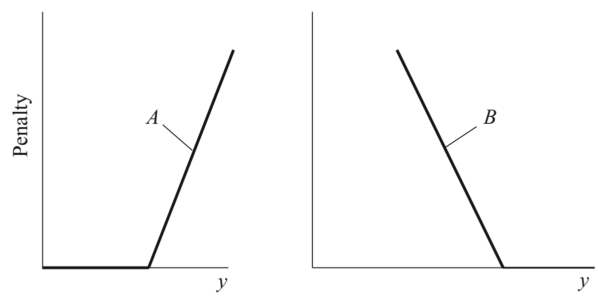

Fig. 1. Form of the penalty functions.

In solving the problem of controlling the tempering process the type of article being produced, which influences the value of the factor variable x_{13} (number of flows), is considered to be given. During the production process, perturbations can change the coefficients in the regression equations, which can make the constraints (5) – (8) incompatible, and the problem formulated will not have a solution.

In this connection a control algorithm where the "rigid" constraints (5) – (7) are replaced by "non-rigid" constraints by reducing the mathematical programming problem to solving an unconditional minimization problem using the method of penalty functions [2]. The penalty function F of the following form is chosen as the control criterion:

$$F = \lambda_1 \,\mathrm{abs}\,(\max\,(y_1 - y_{1,\,\mathrm{pr}}\,,\, 0))\,\frac{1}{y_{1,\,\max}} + \lambda_3 \,\mathrm{abs}\,(\min\,(y_3 - y_{3,\,\mathrm{pr}}\,,\, 0))\,\frac{1}{y_{3,\,\min}} + \lambda_2 \,\mathrm{abs}\,(\max\,(y_2 - y_{2,\,\mathrm{pr}}\,,\, 0))\,\frac{1}{y_{2,\,\max}}\,, \tag{9}$$

where λ are weighting factors for the terms of the penalty functions and set equal to 0.33.

The terms in the penalty function (9) are normalized by dividing each one by the admissible value of the indicator (GOST 5727–88), which made it possible to write the penalty in the form of an additive function of dimensionless quantities with the coefficients λ. The terms of the penalty function are piece-wise smooth functions, shown in Fig. 1.

The first and third terms in the expression (9) have the form of the penalty function A. The penalty is imposed when the indictor y exceeds a prescribed value y_{pr}. The maximum number of fragments and their largest length are such indicators. The second term in the expression (9), limiting the minimum number of fragments during the tests, has the form of the function B. A penalty is imposed in cases when the number of fragments becomes less than a prescribed amount $y_{3,\,\mathrm{pr}}$. The slope of the functions determines the rate of imposition of the penalty; it is established by adjusting the coefficients λ. Figure 1 shows an example of a change of the value of the penalty in proportion to the deviation of the parameters from the prescribed value ($y - y_{\mathrm{pr}}$).

The control problem consists in searching for a tempering regime where the penalty functions (9) assumes the minimum value. The penalty function (9) equals zero when each term is zero. The search for the optimal regime was made using a coordinate descent method [2]. The region of search with respect to each regime variable (coordinate) was established by setting their range of variation. This range was taken to be the range of variation of the regime variables under industrial process conditions. The size of a stepped change of the regime variables during the search was adopted taking into account the accuracy of their measurement in a manner so that several steps could be taken in a fixed range of variation of the regimes.

The algorithm described above was used to model the control algorithm used for tempering glass. The experiment was performed by using retrospective data on the operation of the tempering furnace during the production of colorless, curved, side window glass for automobiles. The objective of the experiment was to evaluate the possibility of increasing the quality of the glass produced by optimizing the tempering regime.

In the modeling, requirements were prescribed for the quality of the tempered glass. These requirements are given in Table 1. The search range for the regime variables was taken as their range of variation under the conditions of commercial operation of the tempering furnace.

The stepped change of the regime parameters in the search was chosen to be 10% of the range of variation. The range of variation of the regime variables in the modeling process are presented in Table 2.

The modeling confirmed that the quality of the glass produced can be increased. The comparative data of the simula-

TABLE 1.

Parameter	Value		
	coded	prescribed	admissible
Number of fragments:			
maximum	y_1	235	400
minimum	y_3	102	40
Largest length of fragments	y_2	39	75

TABLE 2.

Regime (factor) variable	Value			Stepped change
	coded	minimum	maximum	
Vault temperature in chamber 2 in zone 2	x_6	599	645	5
Bottom temperature:				
in chamber 3 in zone 11	x_9	599	654	5
in chamber 4 in zone 12	x_{11}	599	656	5
Interval 2 left-hand side	x_{18}	0.35	0.4	0.00025
Punch height	x_{19}	5	18	0.065

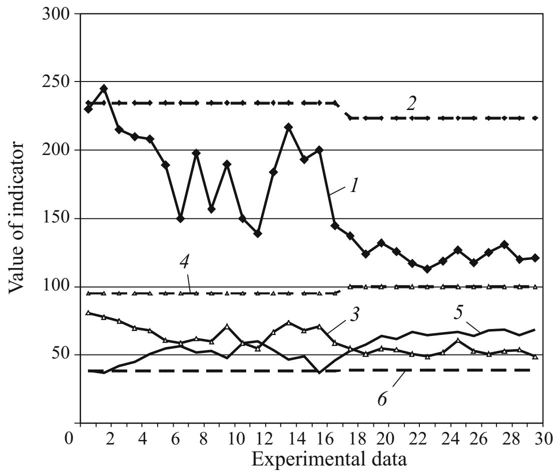

Fig. 2. Number and size of the glass fragments in tests: *1*) maximum number of fragments (actual number); *2*) maximum number of fragments (results of modeling); *3*) minimum number of fragments (actual number); *4*) minimum number of fragments (results of modeling); *5*) maximum length of fragments (actual length); *6*) maximum length of fragments (results of modeling).

tion of the control algorithm with manual insertion of the tempering process are presented in Table 3. As one can see from Table 3 the proposed control algorithm makes it possible to produce tempered glass with prescribed quality requirements (see Table 1).

The results of the tests of the glass for breakage are presented in Fig. 2. Evidently, the maximum and minimum number of fragments and their largest length stabilize as compared with the manual insertion of the tempering process.

The characteristics of the glass stabilize as a result of adjusting the tempering regimes and holding them at the computed levels. Comparative data obtained on the tempering regimes by modeling with manual insertion of the process are presented in Table 4.

The thermal regime of the tempering furnace varies very little, by no more than 6%. The punch height is substantially corrected to lower values. It is corrected by changing the number of glass process flows from 1 to 2 with the height set from 8 to 6 mm. The number of glass flows x_{13} depends on the type of article produced. This factor was studied in the control problem as a planned prescribed quantity.

TABLE 3.

Parameter	Coded value	Modeling results		Manual insertion of the process	
		average value	standard deviation	average value	standard deviation
Number of fragments:					
maximum	y_1	230	5.6	161	41
minimum	y_3	97	2.5	61	9
Largest length of fragments	y_2	39	0.2	56	10

TABLE 4.

Regime (factor) variable	Coded value	Modeling results		Manual insertion of the process	
		average value	standard deviation	average value	standard deviation
Vault temperature in chamber 2 in zone 2	x_6	618	5	627	11.5
Bottom temperature:					
in chamber 3 in zone 11	x_9	649	0	612	16.3
in chamber 4 in zone 12	x_{11}	600	0	614	18.3
Interval 2 left-hand side	x_{18}	0.375	0	0.385	0.02
Punch height	x_{19}	7	1	14.9	4

The simulation modeling performed showed that further improvement of the mechanical properties of the glass produced is possible. It was also shown that modeling is helpful for developing corrective actions in quality management systems in the production of tempered glass.

REFERENCES

1. R. I. Makarov and E. V. Suvorov, "Mathematical description of the process of tempering of automobile glass," *Steklo Keram.*, No. 5, 12 – 14 (2009); R. I. Makarov and E. V. Suvorov, "Mathematical description of the toughening of passenger vehicle window glass," *Glass Ceram.*, **66**(5 – 6), 162 – 164 (2009).
2. Yu. M. Korshunov, *Mathematical Foundations of Cybernetics* [in Russian], Énergiya, Moscow (1972).